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Elastic image registration

5   The present invention relates to the field of digital imaging, for example, in the field of medical imaging. In particular, the present invention relates to a method of registering a first image (e.g. a floating image) and a second image (e.g. a reference image), an image processing device and to a computer program for registering a first image and a second image.

10   When two images of the same object have been taken from different projections or at different points of time, or during different moving stages of the object of interest, or when two images do not come from the same object, but from objects of the same class (for example, two faces or two brains), it may be highly desirable to establish correspondences. Two classes of deformations have to be compensated in order to establish these correspondences: rigid deformations resulting from translational

15   and rotational movements of the object imaged and non-rigid deformations resulting from elastic deformations of the object imaged. An example of such an application is to match a brain with an anatomical atlas in order to automatically find abnormalities or to label the brain with anatomical names. Another example is to observe the deformation over the time of, for example, a beating heart or to register images of a deformable

20   region of a patient (for example, abdomen) taken at different times. Another example is the combination of images acquired with different modalities such as Computer Tomography (CT), Magnetic Resonance Imaging (MRI), Ultra Sound (US), Positron Emission Tomography (PET), Single Photon Emission Computed Tomography

25   (SPECT) to improve the diagnostic process through the combined analysis of anatomical and physiological information.

          It is an object of the present invention to provide for an improved image

30   registration.

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According to an exemplary embodiment of the present invention as set
forth in claim 1, the above object may be solved by a method of registering a first
image and a second image, wherein at least one first landmark is selected in the first
image and at least one second landmark is selected in the second image. Then, these

5   first and second images are registered by using a similarity value, which relates to a
similarity of a first region in the first image determined by at least one first landmark
and a second region in the second image determined by at least second landmark. The
first and second landmarks correspond to each other.

In other words, according to this exemplary embodiment of the present

10   invention, landmarks, for example in medical applications anatomical landmarks, are
automatically or manually selected in the images. These landmarks are used to define
corresponding regions in the images. For example, in angiopraphic images relating to
different heart phases, cross points of the LAD (left anterior descending) and the LCX
(left circumflex) may be used as landmarks in the different phase images. Then, a

15   similarity value is determined to express a similarity between the region indicated by
the first landmark(s) in the first image and the region indicated by the second
landmark(s) in the second image. This similarity value is used to register the images.

Corresponding landmarks in the first and second images are landmarks
which, for example, for anatomical applications, mark the same or corresponding

20   anatomical structures in the first or second images. I.e. corresponding landmarks in the
first or second images are points or regions ideally to be registered on each other.

According to another exemplary embodiment of the present invention as
set forth in claim 2, the first and second landmarks are selected in accordance with a
qualifying function. This means that, for example, only the most significant landmarks,

25   i.e. only the most significant corresponding features are selected as landmarks. In other
words, this exemplary embodiment of the present invention focuses the computational
work on few but significant landmarks, for example, in areas where needed due to large
and highly non-linear deformations and/or well delineated anatomical structures
allowing for unambiguous and precise registration. It should be noted that the

30   landmarks may be selected interactively or automatically.

Advantageously, according to this exemplary embodiment of the present

invention, the speed and robustness of the image registration may be improved by concentrating only on significant landmarks and image areas showing highly non-linear deformations.

According to another exemplary embodiment of the present invention as set forth in claim 3, a local deformation is determined for each landmark in the first and second images. These local deformations are expanded into a global deformation for the images. The global deformation may be used to perform the registration.

According to another exemplary embodiment of the present invention as set forth in claim 4, a similarity value is determined to describe a similarity between respective regions in the first and second images defined by the landmarks in the first and second images. This is done by using the global deformation fields. Advantageously, by this, a similarity of defined regions in the first and second regions may be determined and regions may be identified where the similarity is not yet sufficient.

According to another exemplary embodiment of the present invention as set forth in claim 5, for regions where the similarity is not yet sufficient, a new landmark is defined in the first and second image and the above described method may be iteratively repeated, i.e. for the new sub-regions defined by the new landmark, new sub-similarities with sub-similarity values are determined by using a local deformation field of this new landmark, which is expanded to a global deformation field for the image. Then, all the newly defined sub-regions are tested as to whether a respective similarity value meets with a pre-set threshold and if not, according to this exemplary embodiment of the present invention, new landmarks or new regions may be iteratively defined.

Due to the fact that the refinement process is always limited to the region with insufficient similarity and is not applied to the whole images, the computational efforts may be reduced. Furthermore, by either automatically or interactively performing this iterative refinement, it allows for a very accurate registration.

According to another exemplary embodiment of the present invention as set forth in claim 6, the method is iteratively repeated until all similarities of all regions and all sub-regions exceed a pre-set threshold value.

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According to another exemplary embodiment of the present invention as set forth in claim 7, the method is applied in medical imaging on one of CT data sets, MRI data sets, PET data sets, SPECT data sets, and US data sets.

According to another exemplary embodiment of the present invention as
5   set forth in claim 8, an image processing device is provided, allowing to perform a non-rigid image registration method by an iterative refinement process based on landmarks and a similarity value such as a gray value based measurement of a region in the images.

Advantageously, the image processing device according to this
10   exemplary embodiment of the present invention has an improved registration speed and provides for a very accurate and robust registration of the first and second images.

According to another exemplary embodiment of the present invention as set forth in claim 9, a computer program is provided for registering a first image and a second image. The computer program may be written in any suitable programming
15   language, such as C++ and may be stored on a computer readable device, such as a CD-ROM. However, the computer program according to the present invention may also be presented over a network such as the WorldWideWeb, from which it may be downloaded, for example, into the internal working memory of a processor.

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It may be seen as the gist of an exemplary embodiment of the present invention that a non-rigid image registration is performed by an iterative refinement process based on landmarks combining local template matching. An example for a local template matching is described, for example, in P. Rösch et al, "3D respiratory motion
25   compensation by template propagation" in T. Dohi and R. Kikinis, editors, "Proceedings of the 5th international conference on medical image computing and computer-assisted intervention" – MICCAI 2002, pages 639-646, Springer, 2002, which is hereby incorporated by reference.

The image similarity in the respective regions may, for example, be
30   determined in accordance with J. V. Hajnal et al, editors, "Medical image registration", CRC Press, 2001, which is hereby incorporated by reference. The method focuses the

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computational work on few but significant landmarks and automatically refines the
deformation field only in areas where needed due to large and highly non-linear
deformations and/or well delineated anatomical structures allowing for unambiguous
and precise registration. When A denotes an image that has to be registered with a

5   reference image B, starting from a few but significant landmarks, image A is tiled with
simplices P_A spanned by $d+1$ (d = dimensionality of the data set) neighboring
landmarks. A global deformation field D is constructed by locating the landmarks in B
based on local (for instance affine) deformations in their neighborhoods. Every simplex
(region defined by the landmarks) P_A is transformed into a simplex $P_B = D(P_A)$ and the

10   similarity of, for example, the gray values of image A lying in P_A and the gray values
of image B lying in P_B is estimated using, for example, mutual information or cross-
correlation. If P_A and P_B are not sufficiently similar, a new landmark is located in P_A
and P_A is divided into a plurality of $d+1$ smaller simplices. Advantageously, due to this,
the tiling is iteratively refined until a desired similarity is achieved, resulting in a tiling

15   grid that automatically adapts itself to local non-linearities and, for example, to
anatomical structures.

        These and other aspects of the present invention will become apparent
from and elucidated with reference to the embodiments described hereinafter.

        Exemplary embodiments of the present invention will be described in the

20   following, with reference to the following drawings:

Fig. 1   shows a schematic representation of an image processing device
         according to an exemplary embodiment of the present invention,

25   adapted to execute a method according to an exemplary
         embodiment of the present invention.

Fig. 2   shows a simplified flow-chart of an exemplary embodiment of a
         method according to the present invention, which may be
         performed in the image processing device depicted in Fig. 1.

30   Figs. 3 to 6 show simplified sketches of images and indicated operations
         performed on the images according to an exemplary embodiment

of the method according to the present invention.

Fig. 7   shows two images as examples of a global elastic registration during a respiratory motion of the respiratory system performed in accordance with the exemplary embodiment of the method according to the present invention.

Fig. 1 depicts an exemplary embodiment of an image processing device according to the present invention, for executing an exemplary embodiment of a method in accordance with the present invention. The image processing device depicted in Fig. 1 comprises a central processing unit (CPU) or image processor 1, connected to a memory 2 for storing images or similarity values used or generated during the method. The image processor 1 may be connected to a plurality of input/output, network or diagnosis devices, such as an MR device or a CT device. Furthermore, the image processor 1 may be connected to an ultrasonic scanner. The image processor is furthermore connected to a display device 4 (for example, a computer monitor) for displaying information or images computed or adapted in the image processor 1. An operator may interact with the image processor 1 via a keyboard 5 and/or other input/output devices, which are not depicted in Fig. 1.

Fig. 2 shows a flow-chart of an exemplary embodiment of a method for registering a first image and a second image.

In the following, the present invention will be described with reference to medical imaging, where the landmarks relate to anatomical features in the images and/or to areas having large and highly non-linear deformations and/or well-delineated anatomical structures allowing for an unambiguous and precise registration. However, it should be noted that the present invention may also be applied to non-medical applications, for example, in material testing or quality control, where images of actual products are compared to reference images. Also, this technique may be used for image recognition systems, for example, where faces filmed are to be matched with pre-registered faces to identify the faces or persons.

In short, the method according to this exemplary embodiment of the

present invention, described in the following with reference to Fig. 2 relates to a non-rigid image registration by an iterative refinement process based on anatomical landmarks combining local template matching and gray value based measurement of image similarity. Let image A denote a floating image which has to be registered with a reference image B. Starting from few but significant landmarks (selected interactively or automatically), image A is tiled with simplices P_A spent by $d+1$ (d = dimensionality of the data set) neighboring landmarks. A global deformation field D is constructed by locating the landmarks in image B based on local (for instance affine) deformations in their neighborhoods. Every simplex P_A is transformed into simplex $P_B = D$ (P_A) and the similarity of the gray values of image A lying in P_A and the gray values of image B lying in P_B is estimated using, for example, mutual information or cross-correlation. If P_A and P_B are not sufficiently similar, a new landmark is located in P_A, and P_A is divided into $d+1$ smaller simplices. In this way, the tiling is iteratively refined until a desired similarity is achieved, resulting in a tiling grid that automatically adapts itself to local non-linearities and anatomical structures. The iteration may be stopped when the similarity measure is sufficiently good in all simplices or when a maximum number of refinement steps are reached. The resulting global deformation field is then used to register the given images. The method is open to adjust the qualifying function for selecting the landmarks, the local similarity measure for matching the landmark-centered templates, the global similarity measure for estimating the similarity of the simplices, and the type of transformation used for modeling the non-linear deformations to the modalities, anatomical domains and contrast mechanisms involved. This will be described in further detail with reference to Fig. 2.

In Fig. 2, after the start in step S1, where, for example, the images to be registered are acquired, in step S2 a set (a plurality) of significant landmarks $\{L_i\}$ is selected in both images A and B, which can be unambiguously assigned or allotted to each other, i.e. which unambiguously correspond to each other. A significance of the landmarks may be hereby determined by means of a pre-determined qualifying function. With these landmarks L_i, a simplex tiling $\{P_i\}$ of the images is determined. For a two-dimensional image, the simplices are triangles, and for a three-dimensional image, the simplices are tetrahedrons. This is shown in further detail in Fig. 3, depicting

image A or image B, where five landmarks L_1 to L_5 have been selected. As may be taken from Fig. 3, the landmarks are connected to each other by a line, such that simplices (here triangles) are formed, which tile the image region. This may also be referred to as simplex tiling.

5   As indicated above, the selection of the landmarks L_i may be performed automatically or interactively by an operator. For performing such landmark selection automatically, the above qualifying function may be applied, for example, detecting the brightest spots in the images or a certain gradient in the image.

          Then, in the subsequent step S3, local deformation fields D_i $(L_i,\ U_i)$ are
10 determined for each landmark L_i. In other words, surrounding each landmark L_i, a local deformation field D_i $(L_i,\ U_i)$ is determined in the vicinity or region U_i surrounding the respective landmark L_i.

          Form, size and/or dimensions of the region U_i is set such that there is sufficient structure, i.e. sufficient image energy in the region U_i allowing to
15 unambiguously determine the local deformation. Furthermore, size, form and/or dimension of U_i is selected such that the local deformation may be sufficiently approximated by an affine transformation.

          This is shown in further detail in Fig. 4, showing regions U_1 to U_5 surrounding the respective landmarks L_1 to L_5 . As may be taken from Fig. 4, the shape
20 of the regions U_1 to U_5 is circular. However, it should be noted that also other shapes, such as rectangles may be applied. Within these regions U_1 to U_5, the respective local deformation fields D_1 $(L_1,\ U_1)$ to D_5 $(L_5,\ U_5)$ are determined.

          In the subsequent step S4, the local deformation fields D_i $(L_i,\ U_i)$ are expanded to a global deformation field on area I. In other words, the local deformation
25 fields D_i $(L_i,\ U_i)$ are extended to a global deformation D onto the whole image area I in image A.

          According to an exemplary embodiment, by varying the way the local deformation fields D_i (L_i,U_i) are expanded to a global deformation field D, the method may be adapted to the respective application. For example, Gauss functions, polynomial
30 functions, elastic functions or splines may be used to perform such expansion.

          In the subsequent step S5, a similarity $S_i = S(B|_{D(P_i)}, D(A)|_{D(P_i)})$ is

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determined. In other words, in each tile, region or part P_i of the tiling, a similarity S_i for

expressing a similarity between the reference image $B|_{D(P_i)}$ and the transformed floating

image $D(A)|_{D(P_i)}$ or between the transformed reference image and the floating image.

Advantageously, the similarity value is selected such that it increases with an increasing

5   conformity between the images and is monotonic to a maximum value. Then, in the

subsequent step S6 it is determined whether there is a simplex P_j with $S_j \leq \Sigma$.

A pre-selected value Σ of the similarity value S determines in which

parts of the tiling $\{P_i\}$ i.e. in which simplex, the conformity between the reference

image B and the transformed floating image A is not yet sufficient. In case it is

10   determined in step S6 that there is a simplex P_j with $S(P_j) < \Sigma$, then, the method

continues to step S7, where a refinement is performed. Otherwise, the method continues

to step S8, where it ends.

In step S7, in the simplex P_j with $S(P_j) < \Sigma$, i.e. in the simplex to be

refined, a new landmark is selected. According to an exemplary embodiment of the

15   present invention, shown in Fig.5, the new landmark L_6 is selected in accordance with

the qualifying function such that it is the most significant landmark L' in the simplex P_j

. This landmark is added to the set of landmarks $\{L_i\} = \{L_i\} \cup L_6$. With the new

landmark L_6, the simplex P_j is tiled. Here, L_6 is connected to each vertex (landmarks L_2,

L_4, L_5) by a straight line. By this, for a two-dimensional image, three new triangles are

20   generated and for a three-dimensional image, four new tetrahedrons are generated. In

general: $(d + 1)$ new simplices are generated for d special dimensions. In the set of

simplices $\{P_i\}$, the simplex P_j is replaced by the $(d + 1)$ new simplices. Then, with the

new set of landmarks $\{L_i\}$ and set of simplices $\{P_i\}$ the iteration returns to step S3,

wherein, for the pre-existing landmarks and the pre-existing regions U_i, the local

25   deformations D_i are maintained. The method iteratively continues until there is no

simplex left with $S_j < \Sigma$.

Figs. 5 and 6 depict the further processing according to the method

according to the present invention, as described by steps S3 to S7. In Fig. 5, the simplex

P_j with $S_j < \Sigma$ is hatched. For this hatched simplex P_j, defined by landmarks L_2, L_4 and

L_5, where the similarity value is less than a threshold value, a new landmark L_6 is selected. Preferably, as indicated above, the landmark L_6 is a significant or the most significant landmark in the region P_j. Then, by connecting L_6 to the landmarks L_2, L_4 and L_5 of P_j, three new simplices are generated. Then, a local deformation field D_6

5   (L_6, U_6) is determined and the local deformation fields are expanded to a global deformation field. Then, similarity values are determined for each of these three new triangles. In case there is a triangle (here in Fig. 5 the triangle P_F), which similarity value is less than the pre-set threshold value, i.e. $S_F < \Sigma$, a new landmark L_7 is selected in the triangle P_F as shown in Fig. 6. The method iteratively continues until the

10 similarity value for each triangle exceeds or equals the threshold value.

An application example of the above method is depicted in Fig. 7. In Fig. 7, two MR images of the respiratory system are shown in an exhaled (A) (left image of Fig. 7); and in an inhaled state (B) (right image of Fig. 7). A registration by using the landmarks L_{10}, L_{11} and L_{12} does not allow a sufficiently accurate registration of the two

15 images since the movement of the diaphragm cannot be sufficiently reconstructed. Due to that, iteratively, the new significant landmark L_{13} has been added.

Advantageously, the above method allows for a very accurate and reliable elastic registration of single or multi-modality image data sets. It may allow to improve speed and robustness of image registration by concentrating on significant

20 landmarks and image areas showing highly non-linear deformations. Furthermore, it may allow the significant ranking and matching of landmarks, the local and global quality of registration and the type of non-linear transformations to be independently optimized with respect to the modalities, anatomical areas and expected deformations or application areas. It may allow to register very different imaging modalities by

25 incorporating into these significance and quality measures a priori knowledge about the anatomy. Due to the focus on few but significant landmarks in conjunction with its automatic and spatial adaptivity to non-linear deformations, the above described invention may be very fast and well suited for real time registration, for example, during interventional procedures. In medical applications, global elastic registration

30 may be required for a variety of clinical applications, where images acquired at different times, with different modalities or different patients have to be aligned.

Important examples of, for example, tumor diagnostics and surgery, where images of different modalities show different aspects of the tumor, a comparison of pre- and post-intervention images, analysis of time series of medical images, matching of individual images with anatomical atlases derived from cohort studies etc. However, it should be

5 noted that the above described invention may also be applied to any two or three-dimensional data sets.